A low temperature bonding process using deposited gold–tin composites

Chin C. Lee and Chen Y. Wang

Department of Electrical and Computing Engineering, University of California, Irvine, CA 92717 (U.S.A.)

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Abstract

Conventional bonding techniques using gold–tin preforms or paste usually require a process temperature near 320 °C to ensure complete melting of the preforms. However, a 320 °C process temperature is too high for many devices such as AlGaAs/GaAs and GaInAsP/InP laser diode chips. We report a technique which needs only 260 °C to produce nearly eutectic Au–Sn bonding. This technique utilizes the unique property of the gold–tin alloy system in that the 232 °C tin melting point is significantly lower than the 280 °C eutectic point and solid state interdiffusion. The bonding medium consists of Au–Sn multilayer composite deposited directly on the object to be bonded. This technology eliminates the requirement of preforms, inhibits tin oxidation and provides good control of bonding layer thickness. Results of bonding of 3 mm × 5 mm GaAs dice show that high quality bondings are obtained as determined by a scanning acoustic microscope. The specimens underwent 40 cycles of thermal shock test between −196 °C and 160 °C without bonding degradation and die cracking. Scanning electron microscopy and energy-dispersive X-ray studies reveal interesting mechanisms of the bonding process. This new process is particularly useful for bonding electronic and optical devices which cannot take a temperature above 260 °C.

1. Introduction

A semiconductor device chip is usually bonded on a substrate or a package. The package together with the die-bonding layer serves the purposes of heat dissipation, mechanical support, and sometimes electrical conduction. Without reliable bonding, the device would fail or incur early failure as a result of inadequate heat dissipation and mechanical strength. Accordingly, the quality of the bonding is as important as that of the device die itself. Commonly used media include soft solder, hard solder, metal-filled epoxy and glass [1–4]. The most common soft solders are Sn–Pb alloys. Commonly used hard solders include Au–Sn, Au–Ge and Au–Si eutectic alloys which have melting temperatures (eutectic points) of 280 °C, 361 °C and 363 °C respectively [5, 6].

Despite the continuing effort in electronic industries to produce better die bonds, voids have persistently existed in the bonding layers [7–18]. For bondings using soft or hard solders, the major factor which inhibits high quality bonding is the segregation and formation of materials such as oxides, carbon and silicon on the molten solder solution [2, 10–14, 19, 20]. These materials form a solid film on the solder solution, which prevents the solution from achieving bonds with the die and the package. The oxide layer which exists on the surface of the as-fabricated solder preform is further enhanced in the bonding process when the preform melts [19, 20]. To break down the oxide film, it is common to use scrubbing in the process. While the scrubbing action does break down the oxide film, it may also induce voids and inhomogeneity in the bonding layer. However, a technique using controlled scrubbing has recently been reported to produce quality bondings of GaAs dice with Au–Sn alloy [21].

In our previous studies, we eliminated the scrubbing and instead used static pressure on the die. Nearly perfect bondings have been achieved on 4 mm × 4 mm GaAs dice and 6 mm × 10 mm silicon dice using Au–Sn eutectic preforms [19, 20, 22–25]. The quality of the bondings was determined by scanning acoustic microscopy (SAM). The specimens underwent 40 cycles of thermal shock between −196 °C (liquid nitrogen) and 160 °C (boiling cyclohexanol) without any die cracking and bonding degradation. Results of a pull test show that the bondings are stronger than the dice themselves. These studies prove that the Au–Sn alloy is indeed appropriate for bonding devices which require extremely high reliability.

Recently, we have developed a new bonding technology using multiple layers of chromium, gold, tin, and gold deposited directly on the back side of dice or on packages [26]. In the multilayer composite, the tin and outer gold layers are deposited in one vacuum cycle, thus preventing the tin layer from oxidation. When the specimens are later exposed to air, the outer gold layer protects the tin from having contact with the air and

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thus greatly reduces tin oxidation, which is the major cause of difficulty in forming good bondings. Accordingly, the new technology eliminates the requirement of solder preforms or paste, and inhibits tin oxidation in the bonding. This technology is achievable mainly because of the unique property of the Au–Sn binary system in that the 232 °C melting point of one of the elements, tin, is lower than the 280 °C eutectic point of the alloy [5, 6]. Using this technology, 4 mm × 4 mm GaAs dice have been successfully bonded on alumina substrates, as verified by SAM [26].

The Au–Sn phase diagram shown in Fig. 1 indicates that the process temperature required for the new technology is above 309 °C to ensure the formation of gold–tin eutectic solution. In our previous experiments, a process temperature of 315 °C was used [26]. Also, the conventional process of using Au–Sn preforms usually needs a temperature above 320 °C to ensure complete melting of the preforms even though the Au–Sn eutectic point is 280 °C. Since Au–Sn eutectic has the lowest eutectic point among the three major hard solders, *i.e.* Au–Sn, Au–Ge and Au–Si, 320 °C seems to be the lower bound of process temperatures using hard solders. However, there are many devices which cannot take a bonding temperature of 320 °C without degradation. They include AlGaAs/GaAs and GaInAsP/InP laser diode chips and other III–V compound devices. Accordingly, a lower process temperature is highly valuable for these devices.

In this paper, we report a technique of reducing the process temperature to 260 °C by modifying the technology of using Au–Sn composites [26]. The resulting bonding layer was found to be nearly Au–Sn (80 wt.%–20 wt.%) eutectic even though the process temperature is below the 280 °C eutectic point. The formation of Au–Sn eutectic can be explained by solid state diffusion at a process temperature of 260 °C. Using this method, 3 mm × 5 mm GaAs dice have been successfully bonded, as verified by the SAM. The specimens underwent 40 cycles of thermal shock test between −196 °C and +160 °C without bonding degradation and die cracking. In what follows, the principle of

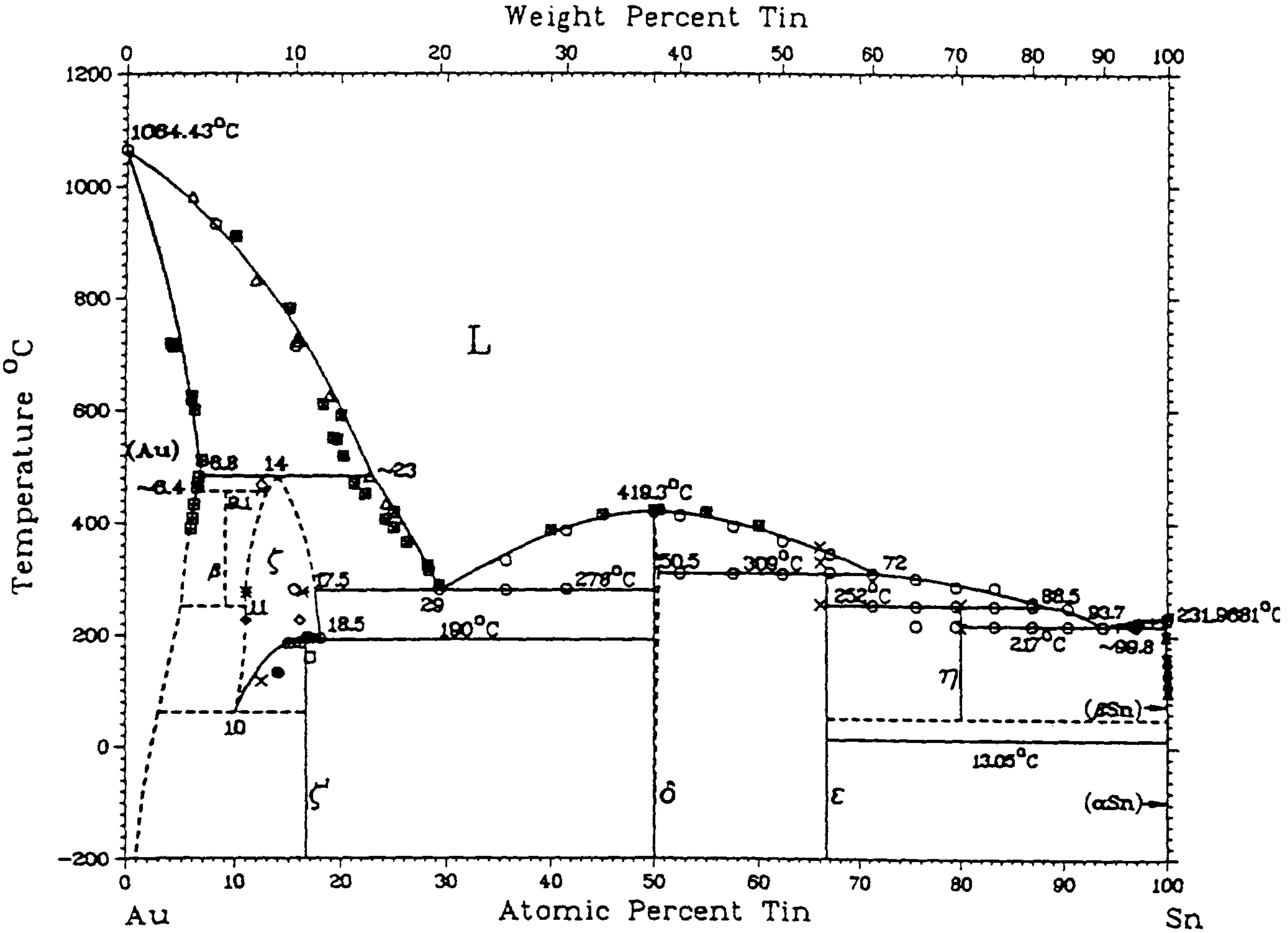


Fig. 1. Gold–tin equilibrium phase diagram [5]. Stable intermetallic compounds are ζ′ (Au_5Sn), δ (AuSn), ε ($AuSn_2$) and η ($AuSn_4$). The alloys with tin composition ranging from 16.5 wt.% to 50 wt.% are mixtures of ζ′ and δ phase.

the technology is briefly described. The experimental procedures are described, followed by results and a short summary.

2. Principle

The principle of the technique is briefly described as follows. Figure 1 shows the Au–Sn phase diagram [5, 6]. Au–Sn alloys having a tin content ranging from 16.5 at.% to 50 at.% are mixtures of Au_5Sn and AuSn intermetallic compounds rather than mixtures of gold and tin. The commonly used Au–Sn eutectic alloy has a composition of 80 wt.% (71 at.%) Au and 20 wt.% (29 at.%) Sn. Figure 2 exhibits the design of the Au–Sn composite. Multiple layers of chromium, gold, tin and gold are deposited on the GaAs wafer to produce a composite in one vacuum cycle to prevent oxidation of the tin layer (layer 3). The chromium layer (layer 1) enhances the adhesion. The outer gold layer (layer 4) prevents the tin layer (layer 3) from having contact with oxygen when the composite is exposed to atmosphere. The alumina substrate is deposited with chromium and gold where the chromium layer enhances the adhesion.

In the bonding process, the die and substrate shown in Fig. 2 are brought into contact with static pressure and heated to 260 °C in hydrogen atmosphere. The Au–Sn binary system shown in Fig. 1 is unique in that the 232 °C melting point of one of the elements, tin, is lower than the 280 °C eutectic point of the alloy. The tin layer (layer 3) of the composite melts as the specimens are heated above the tin melting point. When the tin layer melts, it dissolves the gold layers (layers 2 and 4). The composition of the Cr–Au–Sn–Au composite shown in Fig. 2 is designed so that at 260 °C it becomes an alloy solution or a liquid mixed with solid. For the specific design illustrated in Fig. 2, the Au–Sn–Au composite contains 23 wt.% Au and 77 wt.% Sn. From the phase diagram, it can be seen that at 260 °C the composite becomes a mixture of liquid and solid. Since the die and the substrate are in contact, this mixture wets the gold layer (layer 5) on the substrate and dissolves a portion of it. Since the 260 °C processing temperature is higher than the 252 °C solidus line, as more gold is added, the gold content of the mixture will increase until it reaches 43 wt.% which is the composition of the ε phase. At this point, the mixture becomes solidified since the temperature is less than 309 °C as seen in Fig. 1. If the specimen is suddenly cooled to very low temperature, the bonding layer should consist of 43 wt.% Au. However, if the specimen is held at some elevated temperature such as 260 °C, we speculate that the gold atoms in the remaining gold layer (layer 5) would continue to diffuse into the solid Au–Sn bonding layer until the bonding layer becomes nearly eutectic with a composition of 80 wt.% Au. This type of solid state diffusion and alloy formation is possible in the Au–Sn system because gold and tin interdiffuse quite easily in Au–Sn couples, Au–Sn intermetallic compounds and Au–Sn alloys [27–30].

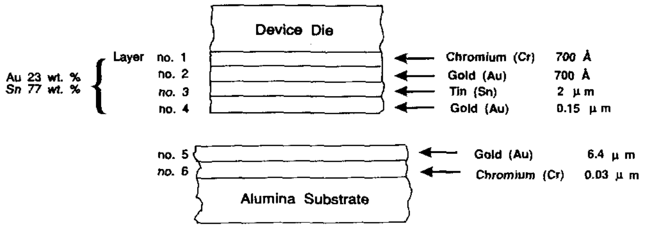


Fig. 2. Multilayer Au–Sn composite structure illustrating the bonding technology (figure not to scale).

We wish to point out that, in the beginning of this study, we only speculated on the possiblility of producing Au–Sn eutectic bonding at a process temperature of 260 °C using the concept of an Au–Sn multilayer composite and the principle of solid state diffusion. We were not certain whether this technology would actually work. On several experiments and careful examination of bonding results, we can conclude that what we speculated actually occurs. In fact, the proposed method turns out to be an excellent technology for bonding devices at a temperature near 260 °C. We also would like to indicate that this method may not be achieved using Au–Ge or Au–Si binary systems because the melting points of the alloy elements are much higher than the eutectic temperature of the alloy.

Besides the advantage of low bonding temperature, the bonding technology does not require the use of solder preforms or paste because the bonding media are deposited directly on the objects to be bonded. For the composite shown in Fig. 2, the tin layer (layer 3) is deposited in vacuum to prevent oxidation. This tin layer is further protected from oxidation by an outer gold layer (layer 4) deposited right after the tin layer in the same vacuum cycle. Furthermore, the amount of the bonding media can be well controlled to achieve accurate bonding thickness.

3. Experimental procedures and results

The polished side of 380 μm thick GaAs wafer was deposited with the Cr–Au–Sn–Au composite structure depicted in Fig. 2. The thicknesses of the four layers in the composite are 0.07 μm, 0.07 μm, 2.0 μm and 0.15 μm respectively. The surface of the composite is very smooth with a peak roughness less than 0.15 μm. If the Au–Sn–Au composite forms a uniform alloy, it would have 23 wt.% gold. After the deposition, the wafer was cleaved into dice 3 mm × 5 mm in size. The substrate used for bonding is 250 µm thick alumina coated with 0.03 µm chromium and 6.4 µm gold. The gold layer was produced by sputtering and has an average grain size of about 2 µm. As a result, its surface is not very smooth and has a peak roughness of 0.4 µm. If the gold layer on the substrate and the Au–Sn composite on the GaAs die form a uniform Au–Sn alloy, the alloy would have 90 wt.% gold, which has more gold than needed to form Au–Sn eutectic.

The substrates were laid on a graphite boat and the dice were placed on the substrates. To ensure good contact between the dice and the substrates, the dice were held down with 0.276 MPa (40 lb in^{-2}) of static pressure using a mechanical tool. The boat assembly was then loaded into a furnace with a flow of hydrogen. The furnace temperature was raised to 260 °C in 5 min and stayed at 260 °C for another 10 min. Afterwards, the boat was pulled out and cooled down to room temperature in 15 min. High quality bondings were consistently obtained. We wish to point out that, in a production environment, the static pressure required can be produced by compressed forming gas rather than mechanical means.

To study the thickness uniformity and to verify the alloy composition of resulting bonding layers, several specimens were cut and polished. Their cross-sections were examined under an optical microscope and by scanning electron microscopy (SEM). The bonding layers are very uniform with a thickness of 8.4 µm. Figure 3(a) shows the SEM image of a portion of a cross-section. We can see that the bonding alloy does not penetrate into the GaAs die or the alumina substrate. Figure 3(b) exhibits the dot element map of the gold produced by energy-dispersive X-rays (EDX) while Fig. 3(c) shows the dot map of tin. We see that the tin atoms originally in the Au–Sn composite have diffused and spread over the entire bonding layer including the gold layer on the substrate. To determine the alloy composition, EDX plots for gold and tin were obtained. Figure 4 gives the gold weight percentage and tin weight percentage across the bonding layer extending from the substrate top surface to the GaAs back side. Two sets of data are shown which were measured along different traces across the bonding layer. Measurements along other traces gave similar results. From the EDX results given in Fig. 4, we observe that the gold composition ranges from 75 wt.% right underneath the back side of the GaAs die to 100 wt.% right above the alumina substrate. Since the original Au–Sn composite contains 23 wt.% Au and 77 wt.% Sn, on melting at 260 °C it forms a mixture of liquid and solid. According to the phase diagram shown in Fig. 1, at 260 °C this mixture would dissolve the gold layer on the substrate and eventually become solidified at a gold content of 43 wt.%. However, from the EDX data, the lowest gold weight percentage over the entire bonding layer cross-section is 75% rather than 43%. This strongly suggests that, during the process, the gold atoms of the gold layer on the substrate continue to diffuse into the solid mixture and in the meantime the

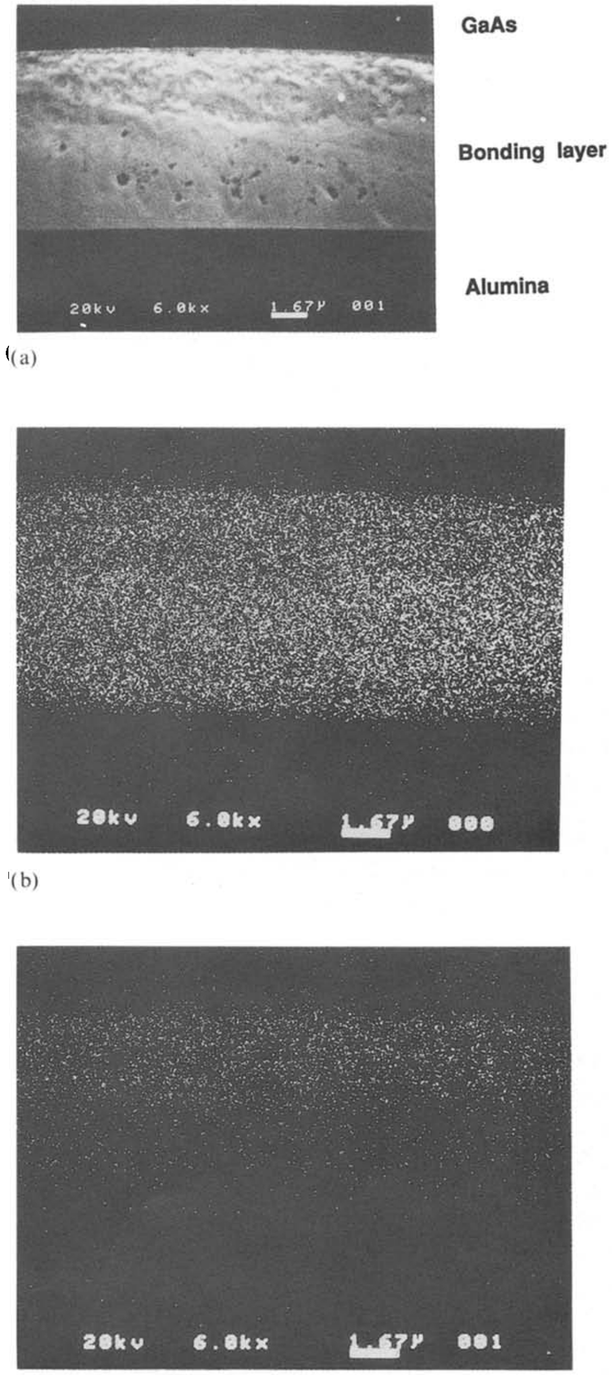


Fig. 3. (a) SEM image of a cross-section of the bonding layer formed by multilayer composite structure using the new bonding technology. (b) The dot element map of the gold produced by EDX. (c) The dot element map of the tin produced by EDX.

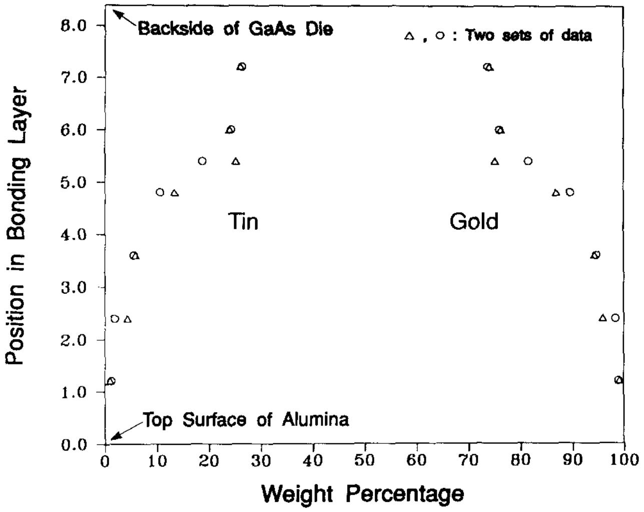


Fig. 4. EDX measurement results of gold and tin along two different traces across the bonding layer extending from the substrate surface to the back side of GaAs die.

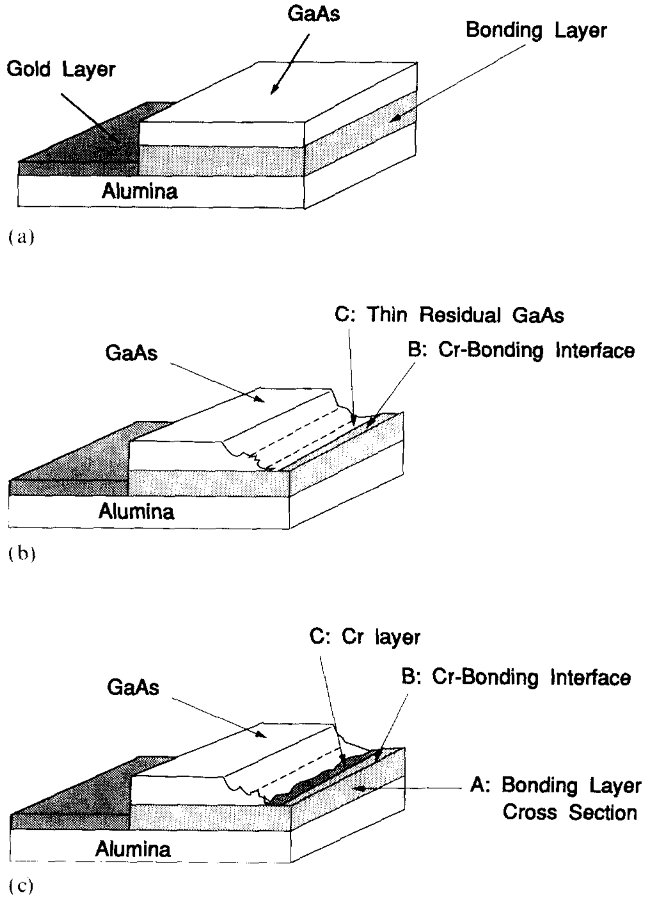
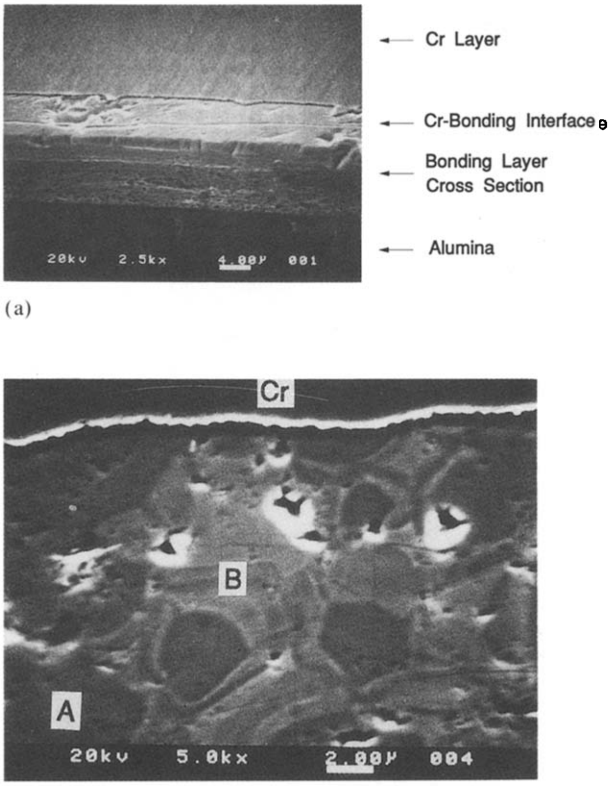


Fig. 5. Specimen preparation procedures (figure not to scale). (a) A device was cut in half and polished in cross-section. Half is shown here. (b) A piece of GaAs die chipped away during the polishing process to remove the GaAs. (c) The thin residual GaAs layer was removed by scrubbing with a cotton swab soaked with weak etching solution.

tin atoms in the mixture continue to diffuse into the gold layer.

In an attempt to study the interface between the GaAs die and the bonding layer, we tried to remove the GaAs dice by polishing and etching. The GaAs etching usually also attacks the chromium layer and removes the tin atoms of the Au–Sn bonding layer. As a result, it is difficult to reveal and expose the interface without changing its composition. We succeeded in removing some GaAs die and the chromium layer of the specimen without changing the composition of the Au–Sn bonding layer. This specimen is half of the sample that was cross-sectioned and whose other half is shown in Fig. 3(a). We first polished the GaAs of the specimen. In the polishing process, a piece of GaAs cracked and came apart as portrayed in Fig. 5. This GaAs piece broke away from the bonding layer at two distinct planes. On an area near the edge of the bonding cross-section indicated as "B" in Fig. 5(b), the GaAs pieces broke away at the interface between the chromium layer and the bonding layer. In a region about 10 μm away from the edge, indicated a "C" in Fig. 5(b), it fractured in GaAs. To remove the very thin residual GaAs layer, weak etching solution was used together with the aid of scrubbing by a cotton swab. The resulting specimen displays three interesting regions indicated in Fig. 5(c), *i.e.* the bonding layer cross-section, the interface right below the chromium layer and the residual chromium layer. These three regions were studied by SEM and EDX. Figure 6(a) shows an SEM image which covers the three regions. We observe that the surface of the chromium layer is extremely smooth and that the alloy solution does not penetrate into the chromium layer, thus indicating that chromium is an excellent diffusion barrier for Au–Sn alloy solutions. The existence of the chromium layer was verified by EDX. To study the grains of the bonding layer, the interface right below the chromium layer was examined by SEM in high contrast' mode. An SEM image is exhibited in Fig. 6(b). We see two distinct grains, dark grains marked as "A" and light grains marked as "B". It should be noticed that the very bright spots in Fig. 6(b) are caused by small cavities. EDX results indicate that the dark grains contain 55 at.% Au and 45 at.% Sn. Thus, these grains are probably formed by AuSn intermetallic compound. The light grains contain 83 at.% Au and 17 at.% Sn. This indicates that they are formed by Au_5Sn intermetallic compound. We should point out that Au–Sn alloys having a tin content of 16.5 at.%–50 at.% are mixtures of Au_5Sn and AuSn compound rather than of gold and tin [5, 6]. Results of our study confirm this mixture of Au_5Sn and AuSn for the bonding layer.



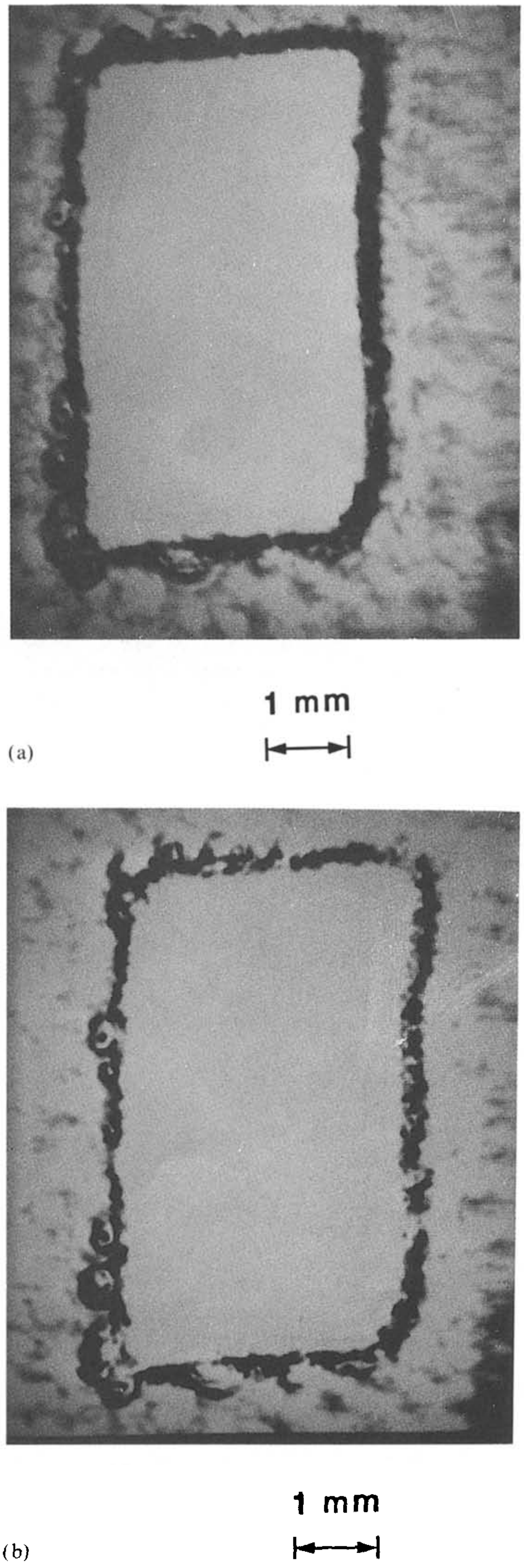
(a)

(b)

Fig. 6. (a) The SEM image of the sample after the procedures given in Fig. 5. Three interesting regions are shown: the bonding layer cross section, the interface right below the chromium layer, and the chromium layer. (b) The SEM image of the interface right below the chromium layer exhibiting the grains of the Au–Sn alloy.

To examine the quality of the bonding, a transmission scanning acoustic microcsope was used to image the specimens [19, 20]. Operating at a frequency of 130 MHz, the scanning acoustic microscope has a spatial resolution of 25 μm. We have previously established that the quality of bondings determined by the SAM images correlates well with their shear strength [19, 20]. Thus, SAM has become a valuable tool to evaluate non-destructively bonding quality and to develop better bonding techniques. Figure 7(a) exhibits the SAM image of a specimen which has near-perfect bonding. Dark areas in the image indicate voids or defects. No voids larger than 25 μm were detected. For the specific specimens in this study, voids smaller than 25 μm are hard to detect with the present SAM technique. Thus, some voids smaller than 25 μm certainly may exist in the bondings. However, we speculate that these small voids would have little effect on the quality of the bonding.

To study the reliability of the bonding further, ten specimens were subjected to thermal shock test between −196 °C (liquid nitrogen) and 160 °C (boiling cyclohex-



(a)

(b)

Fig. 7. (a) SAM image of a GaAs die perfectly bonded to an alumina substrate using gold and tin composite structure before thermal shock test. (b) SAM image of the same specimen as in (a) after 40 cycles of thermal shock test between −196 °C and 160 °C.

anol). After 40 cycles of thermal shock, the specimens were examined by SAM to identify bonding degradation and die cracking. It was found that well-bonded devices remained well bonded and no die cracking was detected after the test. Figure 7(b) displays the SAM image of the specimen shown in Fig. 7(a), after the test. We see that no bonding degradation is observed.

4. Summary

In summary, we have developed a 260 °C bonding process using deposited Au–Sn multilayer composites. This 260 °C process temperature is lower than the Au–Sn eutectic point of 280 °C. Thus the new process is possible because of solid state interdiffusion and the unique property of Au–Sn system in that the 232 °C melting point of tin is lower than the 280 °C eutectic point. GaAs dice 3 mm × 5 mm in size have been successfully bonded on alumina substrates. The bonding quality was examined by a scanning acoustic microscope. Nearly perfect bondings have been achieved. Results of SEM and EDX studies confirm the bonding principle and reveal interesting mechanisms of the bonding process. The specimens were subjected to 40 cycles of thermal shock between −196 °C and 160 °C without degradation and cracking. This process technique is particularly useful and valuable for bonding electronic and optical devices which cannot handle a process temperature higher than 260 °C. Work is underway to reduce the process temperature further down to 235 °C.

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